

THE GALACTIC CENTER: A PEV COSMIC RAY ACCELERATION FACTORY

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ABSTRACT

The cosmic rays below the knee energy (~ 4 PeV) are believed to be accelerated in our galaxy. Just recently, the rather hard diffuse γ -rays at energies of tens of TeV from galactic center observed by HESS experiment are regarded as an indication of PeV proton acceleration. However, such a scenario contradicts to the fact that the γ -ray emission from the point source of galactic center has a break power law spectrum at tens of TeV, which hints that the maximum attainable energy is only ~ 200 TeV. It is important to understand the inconsistency and study the possibility that PeV cosmic ray acceleration at galactic center should account for the apparently contradictory point and diffuse γ -ray spectra.

In this work, we propose that the cosmic rays are accelerated up to $> \text{PeV}$ in galactic center. The interaction between cosmic rays and molecular clouds is responsible for the multi-TeV γ -ray emissions for both the point source and diffuse one today. Enhanced by the small volume filling factor of the clumpy structure, the absorption of the γ -rays leads to a sharp cut-off spectrum at tens of TeV produced in galactic center. Away from GC, the volume filling factor grows up and the absorption enhancement becomes ignorable and pristine γ -ray spectrum is preserved.

As a result, the spectra of γ -ray emissions for both point source and diffuse one can be successfully reproduced under such self-consistent picture. In addition, the spectrum from the point source of galactic center is expected to exhibit a “survived-tail” at ~ 100 TeV, where the absorption cross section starts to decrease. Such a feature distinguishes the absorption model from acceleration model and will be tested by future projects, such as CTA, LHAASO. Neutrinos are simultaneously produced as the γ -rays during PP -collision. With 5 \sim 10 yrs observations, the IceCube and KM3Net experiments will be able to detect the PeV source according to our calculation.

1. INTRODUCTION

It is well known that the Galactic Center (GC), with a supermassive black hole ($\sim 4 \times 10^6 M_\odot$), is a good laboratory for the study of astrophysical phenomena. Historically, there have been many discussions on the possibility that the GC is a dominant source of Galactic Cosmic Rays (GCRs) (Ptuskin & Khazan 1981; Said et al. 1981; Giler 1983; Guo et al. 2013a,b). With the state of art technologies, current γ -ray observations provide unprecedented sensitivity in studying the acceleration activities in GC.

The very high energy γ -rays from hundreds of GeV to tens of TeV in the direction of the GC have been observed by several atmospheric Cerenkov telescopes such as CANGAROO (Tsuchiya et al. 2004), VERITAS (Kosack et al. 2004; Smith & for the VERITAS Collaboration 2015), HESS (Aharonian et al. 2004, 2006a,b, 2008), and MAGIC (Albert et al. 2006). Later observation by HESS found the source spectrum has an exponential cut-off at about tens of TeV with implication of intrinsic origin (Aharonian et al. 2009). This implies that the maximum accelerated energy for proton is ~ 200 TeV as shown (Guo et al. 2013b). The diffusive γ -ray emission is also observed at Galactic Center Disk (GCD) range by HESS experiment (Aharonian et al. 2006a). More interesting thing is that the γ -ray emission is correlation with the density of molecular hydrogen, which is generally regarded as hadronic source. Simultaneously, the spectrum for GC point source is the same with diffusive

one, which may possibly share the same origin: GC supermassive black hole. Just recently, the diffuse γ -ray emissions around GC have been observed by HESS experiment (HESS Collaboration et al. 2016). The result supports that the γ -ray emissions come from $\sim \text{PeV}$ energy proton and the most plausible accelerator is the GC (HESS Collaboration et al. 2016). The problem is how to understand the cut-off in the spectrum of the central source. One possible reason is the absorption of γ -rays by interactions with the ambient infrared radiation field.

The calculations (Zhang et al. 2006; Moskalenko et al. 2006) showed that the absorption effect might not be ignorable at tens of TeV from GC. But it is not sufficient to explain the cut-off of the spectrum in the central source (Aharonian et al. 2009). It is possible that the density of radiation field is underestimated. The infra-red radiation field near the GC may not be homogeneous. As we have known, the Volume Filling Factor (VFF) of the dense material in CND is about 1% (Vollmer & Duschl 2001b, 2002; Fryer et al. 2007). At the central cavity (Jackson et al. 1993; Guesten et al. 1987), the gas density is larger enough for self-gravity to form clumpy structure to overcome the strong tidal shear of the black hole and this will make the VFF even smaller as $\sim 0.1\%$ (Jackson et al. 1993; Genzel et al. 1985). One important consequence is that the infrared radiation component of ISRF should have a similar VFF as the gas material. The reason is that the infrared background light comes from the re-emitting of the gas after absorbing the star

light. A small VFF means that the γ -rays experience much more background photons being generated or passing through the dense gas region. That cause a much stronger absorption and attenuation at high energy. So the observed γ -ray cut-off at tens of TeV can be possible due to the attenuation of ISRF. Away from GC, the VFF grows up, the absorption will become more and more less important.

In this work, we propose that the CR can be accelerated to \sim PeV during the GC activity in past and are producing the high energy γ -rays by PP -collision today. We further suggest that observed sharp cut-off γ -ray spectrum is due to the absorption of ISRF enhanced by their dense clumpy structure in the GC. Considering the density of ISRF and absorption efficiency, the higher energy γ -ray around 100 TeV can escape and the survived tail is predicted, which can be tested by future projects, such as CTA, LHAASO experiments. Simultaneously, the neutrino can be produced during the PP -collision, which can be observed by the IceCube and KM3Net experiments in a few yrs' operation. The paper is organized in the following way. In Sec. 2, we present the detailed modeling of this picture. Sec. 3 is the discussion and Sec. 4 gives the conclusions.

2. MODEL AND RESULTS

Although the overall behavior of GC is quite silent, the observations in X-ray and infrared bands indicate that it still has continuous weak activities (Becklin et al. 1982; Davidson et al. 1992; Dodds-Eden et al. 2009, 2011). During such kinds of activities, the accretion of stars and gas by the supermassive black hole could be effective to accelerate particles. The maximum energy that protons can achieve for diffusive shock acceleration is (Aharonian & Neronov 2005)

$$E_{\max} \sim eBR \approx 10^{14} \left(\frac{B}{G} \right) \left(\frac{M}{4 \times 10^6 M_{\odot}} \right) \left(\frac{R}{10 R_g} \right) \text{ eV} \quad (1)$$

where B is the magnetic field and R is the size of the acceleration region. As in (Aharonian & Neronov 2005), we assume the acceleration takes place within 10 Schwarzschild radii ($R_g \sim 10^{12}$ cm) of the black hole. To accelerate protons to above \sim PeV requires magnetic field strength of tens of G in the acceleration region (Dodds-Eden et al. 2009; Markoff et al. 2001). Such a condition could be reached in the very central region of the GC (Aharonian & Neronov 2005; Eatough et al. 2013). On the other hand, if the acceleration takes place in larger regions, the required magnetic field could be smaller. When the accelerated CRs diffuse out the GC, the hadronic interaction with ISM will happen and produce similar amount of γ -rays and neutrinos. The model calculation is discussed in the following.

2.1. The γ -ray emission in GC with the break spectrum of protons in high energy

The γ -ray emission from the point source in GC has a break power law spectrum at tens of TeV. The best fit of the cut-off can be described by exponential function in high energy (Aharonian et al. 2009). While adopting the traditional model of ISRF, the absorption effect is too small to explain the observed cut-off spectrum of

HESS J1745-290 (Aharonian et al. 2009). The alternative solution attributes it to the intrinsic cut-off, which characterizes the acceleration limit of the flaring event. For comparison, the break spectrum of protons can be simply adopted to Exponential Cut-off (EC) as e^{-E/E_c} or Super-exponential Cut-off (SEC) as $e^{-(E/E_c)^s}$. Where E is the proton energy, $E_c = 200$ TeV is the critical energy and $s \gg 1$ denotes the sharp break. The spectrum of γ -rays are calculated as shown in Fig.1. From this figure, it is clear that the proton spectrum with SEC is better to fit the observation.

Although the γ -ray emission in point source of GC can be explained by adopting the SEC of injection CRs, it is hard to reproduce the diffuse one around GC region under the same scenario. The alternative method, like the absorption in heavy ISRF, should be considered to understand the possible physical mechanism in one unified way.

2.2. γ -ray absorption with an inhomogeneous ISRF in GC

The Galaxy is not transparent to very high energy γ -rays. The main three processes resulting in energy losses of photons are photoelectric effect, Compton scattering and pair production. The photoelectric effect and Compton scattering are negligible for the γ -ray with the energy higher than tens of TeV (Guo et al. 2014). So the dominant contribution to the attenuation comes from the pair production, which leads to the change of the γ -ray spectrum. In this work, the absorption can be divided into two components: within the source region and on the way from the source region to the earth. For the latter one, previous studies (Zhang et al. 2006; Moskalenko et al. 2006) have shown that the absorption is just 10% for 20 TeV γ -rays and 20% for 50 TeV γ -rays, which is far less than what required in order to explain the cut-off spectrum of the point source at GC (Aharonian et al. 2009). Absorption in the GC region might be more complicated and need special consideration. The energy dependent absorption of γ -ray can be described as $e^{-\tau(E)}$, where $\tau(E)$ is the optical depth for γ -ray in energy E . Similar to the work (Zhang et al. 2006; Moskalenko et al. 2006), $\tau(E)$ can be described in the source region as:

$$\tau(E) = \int dr \int d\cos(\theta) \int \frac{dn(\epsilon, R, z)}{d\epsilon} \times \sigma_{\gamma\gamma}(E, \epsilon, \cos\theta) \frac{1 - \cos\theta}{2} d\epsilon, \quad (2)$$

where ϵ is the energy of the ISRF photon, $dn(\epsilon, R, z)/d\epsilon$ is the differential number density of ISRF in GC, $\sigma_{\gamma\gamma}$ is the pair production cross section. The integral of dr is along the radius of GC source.

In fact, the matter and radiation field distribution in GC region is inhomogeneous. The volume surrounding the center cavity and extending from 2 to 7 pc is the Circumnuclear Disk(CND). The VFF of the dense material in CND is about 1% (Vollmer & Duschl 2001b, 2002; Fryer et al. 2007). At the central cavity, the thickness of the disk is $0.4 \sim 0.5$ pc (Jackson et al. 1993; Guesten et al. 1987) and the gas density is much larger than CND. So the VFF is even smaller, such as $\sim 0.1\%$ (Jackson et al. 1993; Genzel et al. 1985). One important

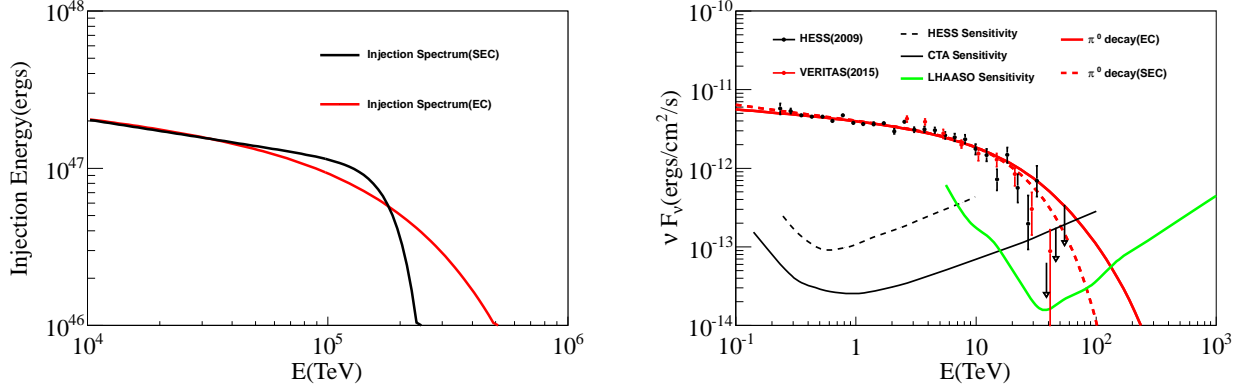


FIG. 1.— Left: the injection spectrum of proton with an EC or SEC at critical energy $E_c = 200$ TeV. Right: The γ -ray emission comparison between model calculation of PP -collisions and HESS observation (Aharonian et al. 2009).

consequence is that the infrared radiation component of ISRF should have a similar VFF as the gas material. In the simplest way, the density of background photons can be described as $n_{ph}(\nu) \propto \frac{4\pi}{c} I_\nu$. $I_\nu \propto \frac{1}{r^2}$ is the intensity of radiation. After considering the VFF, the intrinsic radius of ISRF clump r' can be described as $r' = r/f^{1/3}$, where f is the VFF. It is to say that the density of ISRF I_ν in the source region is boosted to $f^{2/3}$. Based on the optical depth formula 2, one needs to integrate the absorption within the radiation region r' . So compared with the traditional calculation, the absorption should be enlarged by a factor of $f^{1/3}$.

Fig.2 shows the attenuation with different VFF. In this calculation, the injection spectrum of proton is assumed as a power law with the break energy at 4 PeV (left panel of Fig.2) and 100 PeV (right panel of Fig.2). The break energy reflect the maximum energy that protons can achieve in GC activity. The choice of 4 PeV originates from the knee position of all particle spectrum and 100 PeV come from the newest observation of light nuclei (Buitink et al. 2016). It is clear that the attenuation effect can be significantly enlarged in case of a VFF. Taking into account the newly estimated photon density and by adopting a VFF of about 0.1%, the observed spectrum from the point source of GC can be well described. Away from GC, the VFF will grow up, which leads to the smaller VFF of ISRF. In the diffuse emission of GC, the similar calculation is performed with 1% VFF, which is roughly consistent with the observation. The typical features of a survived-tail is expected at ~ 100 TeV for the point source. We hope that the high precise measurements of the γ -ray spectrum from TeV to hundreds of TeV will be performed by future projects, such as CTA (CTA Consortium 2011), LHAASO (Cao 2010), which can give the ultimate decision to our model.

2.3. Neutrino emission

When the observed γ -rays are mainly from the decay of the neutral pions which is the products of hadronic interaction between CRs and ambient gas, similar amount of neutrinos are expected to be produced from the charged pion decay. The γ -ray spectrum may be distorted by the absorption interaction, neutrinos can carry the spectrum of parent CR interaction. Neutrino spectrum can thus provides decisive information to distinguish whether intrinsic acceleration or absorption of ISRF should be re-

sponsible for the cut-off spectrum of γ -ray.

On average, PP -collision produces equal number of neutral pion and charged pion. Each neutral pion decays to a pair of γ -ray and each charged pion decay into two muon neutrinos and one electron neutrino. The initial neutrino flux ratio is approximately $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$ from charged pion decay. However, the flavor ratio is close to $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$ at the earth after vacuum oscillation through traversal of astrophysical distance. So the typical energy of the neutrino ($\nu + \bar{\nu}$) coming from charged pion decay is ~ 0.5 of the γ -ray energy from neutral pion decay.

High energy neutrinos can be detected by neutrino telescopes which use either ice or water as target and detector medium. Neutrino undergoes charge current or neutral current interaction with target matter and produces lepton inside detector (as contained event) or in vicinity of detector (through going event). The high energy muon can generate Cerenkov light while electron and tau may develop to shower which can also generate Cerenkov light for further detection.

There are two modes of muon event rate as one is the contained event and the other is through-going event. The contained event is described as the interaction for neutrino with nucleon inside the detector and given by (Kistler & Beacom 2006; Yuan et al. 2011)

$$\left(\frac{dN_\mu}{dE_\mu}\right)_{con} = kV_{det} \frac{d\Phi_\nu}{dE_\nu} e^{E_\nu/E_\nu^{cut}} \sigma_{CC}(E_\nu) e^{-\tau} \quad (3)$$

where V_{det} is the detector volume, which is adopted to be 1 km^3 ; E_ν^{cut} is the high energy cut-off of neutrino spectrum; the term $k = N_A \rho T < 1 - y(E_\nu) >^{-1}$ take into account observation time (T), normalization of the muon spectrum and the molar density of water (KM3Net) or ice (IceCube). The through-going event is described as the interaction for neutrino with nucleon outside the detector and given by (Kistler & Beacom 2006; Yuan et al. 2011)

$$\left(\frac{dN_\mu}{dE_\mu}\right)_{thr} = \frac{N_A \rho T A_{det}}{\alpha + \beta E_\mu} \times \int_{E_\mu}^{+\infty} dE_\nu \frac{d\Phi_\nu}{dE_\nu} e^{-E_\nu/E_\nu^{cut}} \sigma_{CC}(E_\nu) e^{-\tau} \quad (4)$$

Based on above formula, the total muon event number is calculated for the KM3Net experiment. As shown in Fig.3, it is obvious that the KM3Net or IceCube has po-

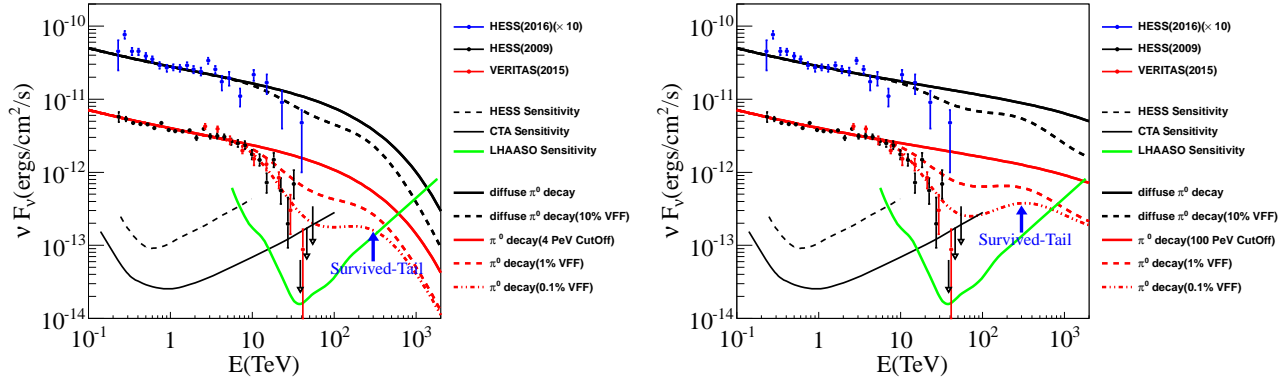


FIG. 2.— The calculated spectrum after the attenuation by considering different VFF.

tential ability to observe GC neutrinos with a few year's operation when the break energy of proton is more than PeV. On the contrary, if the break energy of proton is at ~ 200 TeV, the GC neutrino events can not be separated from atmospheric neutrino background. The observation years to reach a 3σ significance level for different cases are estimated and listed in Table 1. time of 3σ significance level for KM3Net experiment. So the neutrino observation from GC direction can be served to check our model.

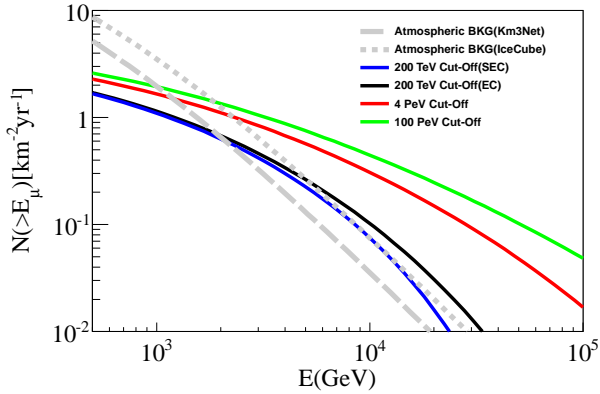


FIG. 3.— The observation of total muon number in one year above an assumed muon energy by KM3Net experiment.

TABLE 1
COMPARISON BETWEEN THE EXPECTED SIGNAL AND THE ATMOSPHERIC NEUTRINO BACKGROUND FOR DIFFERENT BREAK ENERGY OF PROTON

Mode	$E_{th}(TeV)$	$N_{\mu+\bar{\mu}}$	$N_{\mu+\bar{\mu}}^{atm}$	yrs(3σ)
200 TeV energy cut-off	1	1.04	1.90	29.6
	5	0.26	0.13	35.2
	10	0.11	0.03	56.4
4 PeV energy cut-off	1	1.65	1.90	12.1
	5	0.57	0.13	10.0
	10	0.3	0.03	6.9
100 PeV energy cut-off	1	1.92	1.90	8.9
	5	0.75	0.13	5.1
	10	0.45	0.03	5.7

3. DISCUSSION

The effective way to support the VFF of our model is to find out the clump of ISM. In the central region, the mini-spiral is a region with a stellar population cluster and density structure, which consists of four main components: the northern arm, the western arc, the eastern arm and the bar (Kunneriath et al. 2012). In those streamers, it is very bright in NIR wave band and possible PP -collision regime. Recently, ALMA has also Observed some separated clumpy structures (Yusef-Zadeh et al. 2013). We take clump 3 as example to estimate the attenuation of high energy γ -ray. The clumps in the vicinity of the GC are exposed to strong tidal forces which tend to disrupt the clouds, except that the self-gravity is larger enough to overcome the tidal shear. The tidal limit for the clump mass M_{cl} and the clump radius r_{cl} is given (Mathews & Murray 1987; Vollmer & Duschl 2001a):

$$\frac{3}{5} \frac{GM_{cl}^2}{r_{cl}} \geq \frac{1}{5} M_{cl} r_{cl}^2 |f(R)| \quad (5)$$

where, $f(R) = \frac{GM(R)}{R^2}$ and R is the clumps distance to the GC. The mass distribution can be defined as $M(R) = M_0 + M_1 R^{1.25}$, where $M_0 = 4 \times 10^6 M_\odot$ and $M_1 = 1.6 \times 10^6 M_\odot \text{pc}^{-1.25}$. Considering $R=0.12$ pc, $M_{cl} \sim 30 M_\odot$, the critical clump radius $r_{crit} \sim 1500$ AU. Taken the critical radius r_{crit} as the clump size, the calculated spectrum after the attenuation is shown in Fig 4, which is consistent with HESS observation line shape. This further gives the possibility that the enhance density of photon by VFF leads the cut-off of γ -ray spectrum in GC point source.

4. CONCLUSION

GC is a unique laboratory for studying the origin, acceleration and propagation of CRs. Considering the inhomogeneous distribution of the ISRF in the GC, γ -ray absorption is found to enhance largely. If the VFF of the clumpy structure is assumed to be 0.1%, the absorption of the γ -rays can lead to the sharp cut-off at about tens of TeV and a "survived-tail" at about 100 TeV and sharp cut-off for γ -ray spectrum are expected. Away from GC, the VFF grows up and the attenuation becomes less important. The "survived-tail" as the tagged feature can be observed by future projects, such as CTA, LHAASO. High energy neutrino detection is crucial in distinguishing whether the absorption or the intrinsic acceleration is the cause of the γ -ray spectrum cut-off. If our model

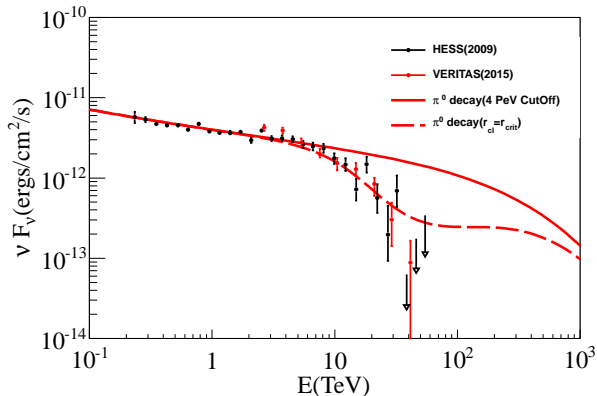


FIG. 4.— The calculated spectrum after the attenuation of Clump 3 with YSO candidate 526817 in it.

is right, KM3Net and IceCube experiments will get 3 σ observation for multi-TeV muon track neutrinos in about 5 \sim 10 yrs observation.

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